Multi-octave spectral imaging in the infrared – a newly emerging approach

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ABSTRACT

A new approach is described for obtaining spectral imagery over a broad range of infrared wavelengths, with high efficiency, and with a single grating element and focal plane array. The approach represents a simplification and mass reduction over the traditional approach involving multiple focal plane arrays, dispersing elements, and optical beamsplitters. The new approach has significant advantages for space-based hyperspectral imagers operating in the infrared over a broad range of wavelengths (e.g., MWIR & LWIR), where the reduction in cryo-cooled mass relative to the multi-channel approach translates into noteworthy savings in cryo-cooling requirements and launch costs. Overlapping grating orders are focused onto a multi-waveband focal plane array in order to create spectral images of a scene simultaneously in multiple wavelength regions. The blaze of the grating is chosen so that all spectral orders are dispersed with high grating efficiency. Such an approach extends the spectral range of dispersive spectrometers to several octaves of wavelength, while preserving the compact packaging and cryogenic requirements of conventional (one octave) instruments. We conclude with a description of a ground-based demonstration of a dual-octave embodiment of the concept.

Keywords: spectral imaging, infrared, focal plane array, electro-optics

1. INTRODUCTION

The challenges of multi-octave spectral imaging in the infrared with down-looking space-based sensors can be divided into those of natural (e.g., atmospheric transmission features) and instrumental type. One of the instrumental challenges is the preservation of high efficiency over a broad range in wavelengths, which for the MWIR and LWIR regions spans more than two octaves of wavelength. Both photovoltaic (PV) detector response and grating efficiency decrease at wavelengths shorter than their optimal values – so a grating-based spectrometer and FPA optimized for the LWIR would suffer from decreased quantum efficiency and grating efficiency in the MWIR. These efficiency losses typically drop below acceptable levels, and the traditional approach for overcoming them has been a multi-channel configuration with grating and FPA "pairs". These channels are optimized for an approximate octave in wavelength, and share a common aperture and FOV through the use of optical beamsplitters, as shown in Figure 1 for two channels. The use of a prism as the dispersion element also restricts the range of useful wavelengths to those for which the angular dispersion of the prism is acceptable[1,2].

Infrared focal plane arrays that image in two wavebands simultaneously (designated "dualband FPA", hereafter) are an emerging technology developed for broad-waveband applications. Noteworthy among their attributes is that spatial and spectral data is collected simultaneously, albeit in only two wavebands. Also noteworthy is that when PV detectors are employed for "Mid-Long" dualband FPAs, high quantum efficiency results in both the MWIR and LWIR, thereby mitigating one of the two key efficiency losses identified above. We address next the nature of a grating-based, dispersive spectrometer with a multi-waveband FPA at its focus, as a generalization of the present dualband FPA capability.

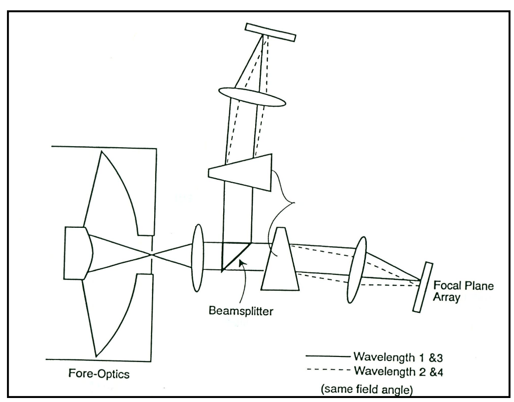

Figure 1. A "classical" two channel spectrometer

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14. ABSTRACT
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Gratings are characterized by high efficiency near their “blaze wavelength”, and values of efficiency that decline rapidly below two-thirds of the blaze wavelength[3]. This feature was mentioned above one of two efficiency losses affecting multi-octave spectral imaging capability. Gratings also have the well-known property of providing multiple, overlapping orders. The existence of overlapping orders has traditionally been viewed as a liability for most applications (with the exception of the CDGS concept, described below), for which unwanted orders falling within the range of useable detector response are “blocked” with spectral filters. An example of this would be a LWIR grating spectrometer which disperses wavelengths from 8 to 14 microns across a two dimensional FPA, with the grating operated in first order. The FPA might also respond to the second order spectrum from 4 to 7 microns that is dispersed over the same region of the FPA; a cryogenically-cooled LWIR spectral filter with wavelength cut-on between 7 and 8 microns would then be used to block the unwanted 4 to 7 micron (and higher order) spectra.

However, there is an attractive feature about the higher grating orders that is relevant to our multi-octave spectral imaging concept. These higher orders enjoy the same blaze wavelength efficiency as the first order. Specifically, a grating with blaze wavelength λ_B has similar efficiency at λ_B / n, where n is an integer. These higher order wavelengths are diffracted by the grating at the same angle, and lay on top of the first order spectrum. We therefore combine the advantage of overlapping grating orders with the capability of multi-waveband FPAs to integrate spectra independently in the various orders, thereby achieving a solution that achieves efficient multi-octave spectral imaging. The properties of this new instrumental concept, used with a dualband FPA, are described in the following section. We note in passing that a related concept that exploits higher grating orders is a cross-dispersion grating spectrograph (CDGS). The CDGS also separates the spectra of overlapping grating orders (thereby enjoying grating efficiencies similar to that for the first order spectrum), but does so with a prism oriented with its dispersion direction perpendicular to that of the grating. The result is several orders of grating spectra separated along the spatial axis of a conventional FPA, and perpendicular to the dispersion direction. This results in a decrease in spatial coverage, since part of the spatial direction on the FPA is used for the higher grating orders. Further, CDGS spectra exhibit curvature within an individual grating order caused by the same prism dispersion that separates the orders.

2. THE DUAL-OCTAVE SPECTROMETER CONCEPT

Figure 2 indicates how the transmission properties of the atmosphere relate to the concept of a dual-octave spectrometer operating in the MWIR and LWIR spectral regions. (The values of atmospheric transmission shown are for a “best-case” atmosphere having very low water vapor content.) The wavelength regions from 3.5 to 6 and 7 to 12 would appear to work well for a dualband FPA having short waveband cut-off and long waveband cut-on (hereafter designated “spectral crossover”) near 6.5 microns, as explained below. Specifically, LWIR cut-off wavelengths approaching 12 microns are found to have levels of dark current lower than that of the signal photocurrents expected for this application (see Section 4); longer cut-off wavelengths having much higher levels of dark current might be problematic for near-term embodiments of the concept. We therefore select 12 microns for the long wavelength extent of the dual-band spectrometer. The corresponding MWIR (second order) spectrometer cut-off is 6 microns; the MWIR response of the dualband FPA needs to extend to 6 microns or longer. We choose to initiate the onset of LWIR spectral coverage at 7 microns rather than at the 6 micron edge of the MWIR coverage. This allows the troublesome wavelengths near the FPA “spectral crossover” (shown schematically in Figure 3) to be dispersed off the FPA, thereby avoiding high levels of spectral crosstalk. The resulting capability shown in Figure 2 can be described as having good coverage of the LWIR atmospheric “window” (although longer cut-off wavelengths would also include the high transmission region between 12 and about 13.3 microns). The capability also includes a significant fraction of relatively good transmission from approximately 3 to 4.2 microns, as well as coverage of the lower transparency region longward of about 4.6 microns. As can be seen in Figure 2, poor dualband FPA performance in the vicinity of the “spectral crossover” does not impact overall system performance, if the crossover is restricted to the atmospheric absorption region between roughly 5.5 and 7 microns.

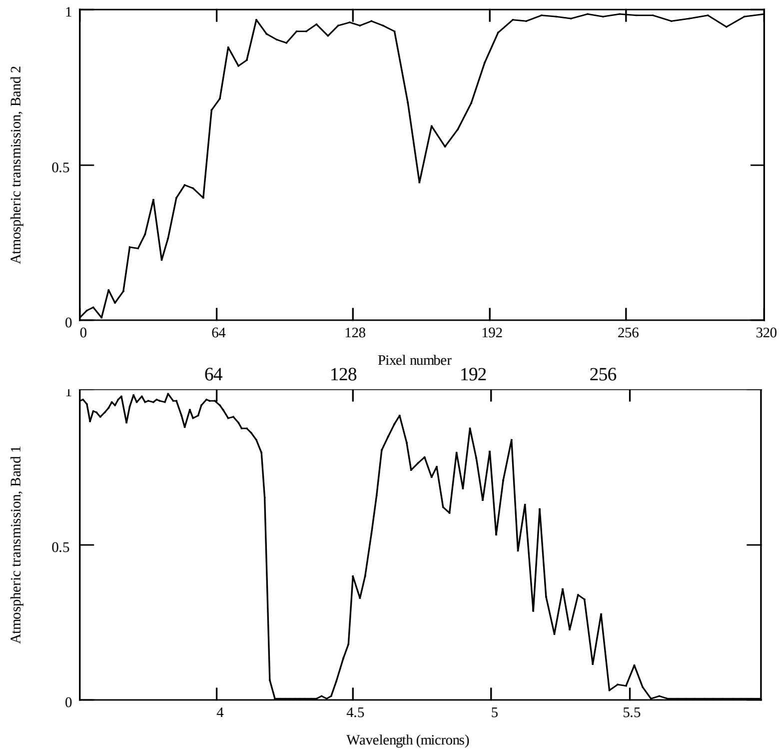

Figure 2. Atmospheric transmission as a function of wavelength for the proposed spectrometer concept. Note correspondence between spectral pixel number and the two wavelength scales (3.5 to 6 & 7 to 12 μm), for an assumed 320

3. GENERAL COMMENTS ON DUALBAND INFRARED FOCAL PLANE ARRAYS

Dualband FPAs have been realized for various "waveband pairs", including MWIR-MWIR (with spectral crossover near 4.3 microns), MWIR-LWIR, and LWIR-LWIR (with spectral crossover near 8 microns). (The dualband quantum well FPA described in Section 6 is a photoconductor, and is unique in having a longer waveband response in the 14 to 15 micron region.) The discussion that follows relates to dualband FPAs of photovoltaic detectors, whose broad wavelength coverage is amenable to dispersive spectral imaging. These FPAs are similar in operation to single waveband FPAs, but each pixel is a site for dualband detection. The shorter waveband material absorbs shorter wavelength photons, and transmits longer wavelength photons to the (deeper) longer waveband. Typically, photocurrents for both wavebands are injected separately into the detector multiplexer circuit, and integrated at separate charge storage sites within the multiplexer. For dualband FPAs fabricated for "simultaneous" operation, both photocurrents are integrated during the same frame time, and typically during the same integration time. In "sequential" operation, one waveband is integrated during one frame time, the other waveband during the next frame time, so that frames of data from the FPA are "waveband interlaced". Waveband-specific values of integration time are easy to implement in the sequential configuration.

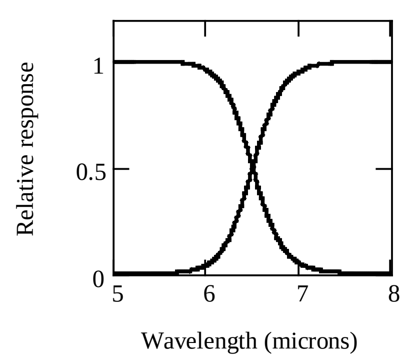

Figure 3. Schematic of dualband FPA "spectral crossover", for which high levels of spectral crosstalk obtain.

Details on the growth and fabrication of the dualband IRFPAs can be found in the literature[4], and are summarized below. In one approach, vapor phase epitaxial growth of the detector material allows for tailoring of the depth profile of both "x" in $Hg_{1-x}Cd_xTe$ and doping density, and therefore of the cutoff wavelengths of the two diodes, grown one on top the other. The LWIR layer is grown on top of (and following) the MWIR layer. The substrate for the dualband film growth is transparent in both the MWIR & LWIR, thereby allowing the resulting IRFPA to be "back-illuminated", with MWIR photons absorbed first, and LWIR photons passing through the

MWIR layer (as through a long-pass spectral filter) and being absorbed near the deeper LWIR junction. Alternate fabrication approaches begin with separate "growths" of the shorter and longer waveband detector material, followed by the interconnection of these with the detector multiplexer using etched vias. Although this approach results in a "front illuminated" dualband FPA, the shorter waveband is "seen" first by incoming photons, as for the vapor phase approach.

4. PERFORMANCE MODELING

We have developed a MathCad™ model for our dualband spectrometer concept that operates over the wavelengths shown in Figure 2. The objectives of this model are to estimate signal photocurrent, as a function of wavelength, that arises from an example scene, and compare this with total noise (also as a function of wavelength). The signal photocurrent estimate also provides a useful comparison with FPA dark current (as shown in Figure 4), and both lead to an estimate for FPA integration times that result in appropriate levels of "filling" the FPA charge integration wells. The scene is typically modeled as a 295 Kelvin greybody having 0.9 emissivity, for the purpose of this estimate of baseline performance. Total noise (in rms electrons) is estimated as a function of wavelength (or spectral pixel number following the correspondence in Figure 2) from photon noise arising from both scene and optics emission, dark current noise, and FPA read-out noise. The calculations have proven useful for evaluating the compatibility of dualband FPAs with the spectrometer concept and for selected optical collecting areas and pixel fields of view. The resulting signal to noise ratios (SNR) are shown as a function of wavelength in Figure 5, for an effective F/4 beam imaged onto a FPA with 50 micron pixels. (This corresponds to a 0.5 meter diameter primary mirror and 25 microradian pixel FOV, for example.) The integration time found for a 75% fill of the charge integration well at a wavelength of 11 microns (where the well fill time is a limiting factor due to the high photon rates at this wavelength) is about 10 millisecs; this value of integration time would be compatible with FPA frame rates in the 50 to 100 Hz regime. The SNR is high except at the shortest wavelengths, where it suffers because of the relatively small number of signal photoelectrons integrated over the time selected to preclude saturation in the LWIR. A custom dualband FPA that allows selection of different (and optimal) values of MWIR and LWIR integration times would lead to improved, shorter wavelength SNR.

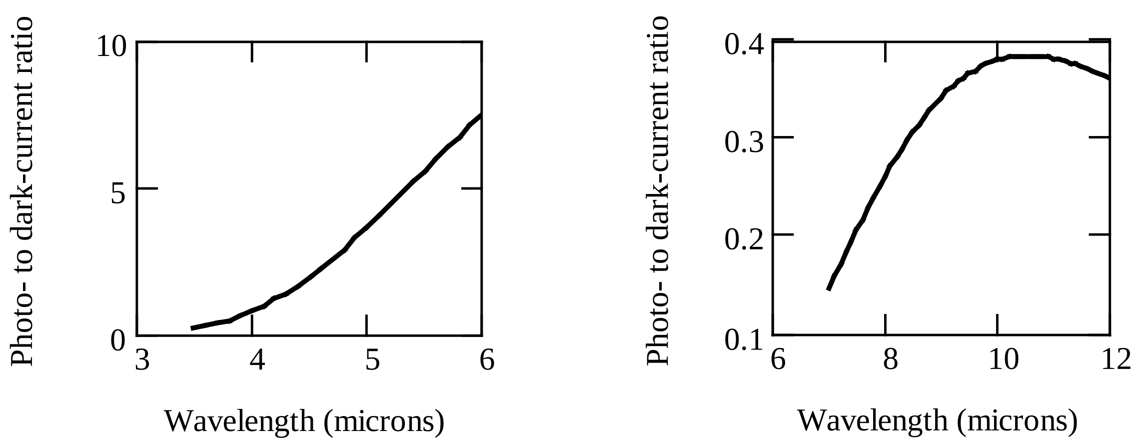

Figure 4. Comparison of signal photocurrent and FPA dark current.

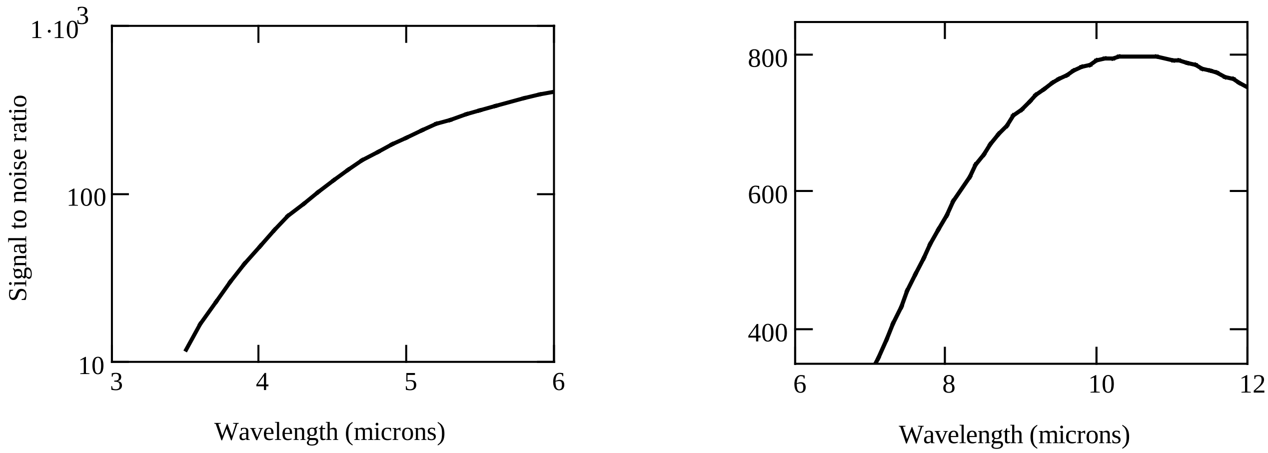

Figure 5. Calculated signal to noise ratios; 10 millisec. integration time. Other details are described in text.

5. SPACE HYPERSPECTRAL IMAGING EMBODIMENT

The multi-octave spectral imager described here would be employed by a down-looking, space-based platform in a mode similar to that for conventional dispersive spectrometers. The spectrometer slit would be oriented perpendicular to the satellite ground trace, so that cross-scan spatial data is obtained by virtue of the spatial axis of the slit as imaged onto the focal plane array, and in-scan spatial data is obtained by virtue of the satellite motion. A multi-waveband FPA that integrates simultaneously in all wavebands would assure simultaneous collection of spectra for each spatial resolution element. Note, the alternative of a *sequentially integrating*, multi-waveband FPA would allow optimization of sensitivity by enabling optimal (and different) values of integration time for the wavebands (with the LWIR typically shortest due to high photon fluxes). We dismiss this approach for most applications, however, because of the resulting loss of simultaneity for a given ground resolution element, and the fact that the signal-to-noise ratio (SNR) in the MWIR can be acceptably high even with a non-optimal ("LWIR-like") integration time. Future FPAs tailored to embodiments of this multi-octave concept would enable improvements in MWIR SNR.

6. A GROUND DEMONSTRATION CONCEPT FOR A DUAL-OCTAVE INSTRUMENT

We have considered salient features of a relatively low cost, "proof of concept" for the dualband spectrometer. We envision a pour-fill Dewar to meet the cooling requirements of both the dualband FPA at a temperature near 60 Kelvin (for acceptably low levels of dark current) and the cooling of the spectrometer optics up to and including the spectrometer slit. A combination liquid helium (LHe) and nitrogen (LN_2) Dewar with a temperature controlled stage for the FPA (and having selectable thermal resistance between the stage and the LHe work surface) meets these requirements. The spectrometer slit would be at the focus of an infrared camera lens mounted external to the Dewar. The camera lens would image over a broad (MWIR to LWIR) range of wavelengths.

A commercially-available electronics package for operating the FPA, and acquiring, displaying, and storing data from the FPA, would comprise the data acquisition system. A "dualband" display capability, i.e., one displaying the pair of spectral images, would be required. In addition to the pixel gain and offset corrections typically included as part of the commercial system, a provision for spectral image corrections would also be required. These corrections include wavelength-dependent variations in instrumental transmission and FPA response that can be determined by observing a laboratory blackbody source. Finally, if the system is used to observe sources through long atmospheric path lengths, provisions for a spectral "atmospheric correction" would be required. A combined instrumental and atmospheric correction would consist of a "vector" of multiplicative correction coefficients which, when applied (in the sense of a vector dot product) to the "vector" of spectral pixel signals, would reproduce a standard (e.g., blackbody) source spectrum. (For the case of rotational

misalignment of the spectral dispersion direction and FPA axes, the "vector" referred to above may well need to transition into an array of multiplicative corrections having dimensions equal to those of the FPA.)

7. A LUNAR STUDY OF THE PROPOSED TECHNIQUE

One of the observational programs made possible with the ground demonstration instrument would be spectral imagery of the Moon. In addition to verifying the level of performance of the ground demonstration concept, the lunar spectral images might be useful for the verification of de-convolution algorithms for hyperspectral imagery. This is significant in that atmospheric properties (both transmission and radiance, if one restricts oneself to the atmospheric window regions) are similar to that for a space-based HSI sensor looking down. Also, the surface of the Moon exhibits variations in radiance due to variations in both temperature (more pronounced) and emissivity (less pronounced). (Earth scenes are presumed to be characterized by more pronounced emissivity and less pronounced temperature variations.) Nevertheless, spectral imagery algorithms that seek to de-convolve atmospheric transmission and radiance from the ground scene radiance could be effectively put to test with the lunar data, by making use of the known lunar temperature distribution over the illuminated hemisphere and maps of lunar features in the visible that correspond to reflectivity variations. Subjecting the algorithms to tests over a range of atmospheric conditions would be both practical and desirable for the verification of algorithm robustness. For our ground demonstration concept, the angular dimensions of the projected spectrometer slit are approximately 0.15 x 18 millirad (F/4 with 170 mm diameter collecting optics, 240 spatial pixels on a 50 micron pitch). Orientation of the spectrometer slit along a lunar diameter should therefore provide spectra of more than 100 spatial locations. Also, drift scans of the slit made possible with the Earth's rotational rate would correspond to approximately 0.5 slit widths per second. Therefore, integration times shorter than about 0.25 seconds should lead to negligible blurring of the slit, and generate more than 100 in-scan positions along a lunar diameter.

We illustrate the ease of acquiring dualband imagery of the Moon with a Quantum Well Infrared Photodetector (QWIP) camera developed by the Jet Propulsion Laboratory. The QWIP camera operates in wavebands at 8.5 and 14 micron wavebands with intrinsic bandpasses of about 1.5 microns. However, given the onset of strong atmospheric CO_2 absorption beyond about 13.5 microns, the effective wavelength of the longer waveband "through the atmosphere" is closer to 13 microns. The camera employs a 100 mm focal length, F/2 camera lens, and the images (shown in Figure 6) were acquired with a 3 msec integration time from a fixed tripod. These images were processed with a one-dimensional interpolation algorithm over column outages in the waveband-interlaced FPA, and atmospheric background was subtracted.

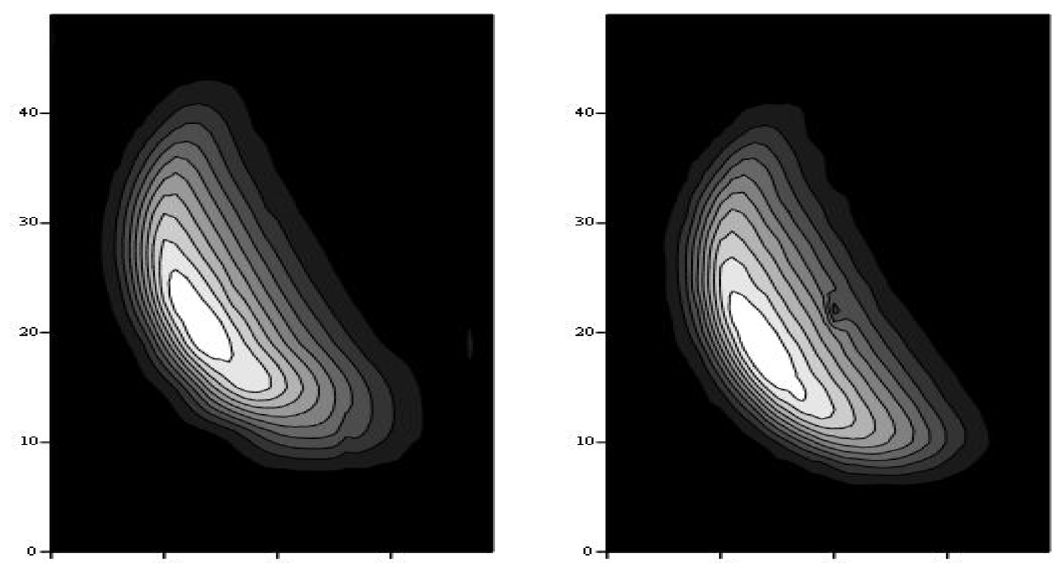

Figure 6. Dualband QWIP images of the moon.

The resulting brightness contours correspond to temperature variations on Moon's front side, with additional projected area effects near the limb. The angular diameter of the Moon at the time of the observations was 0.52 degrees or 9.1 milliradians, to be compared with the approximate 38 pixel samples (at 0.25 milliradian per pixel) observed. These results

help to fuel our imagination for spectral imaging of the Moon with the proposed dual-octave, ground demonstration instrument.

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REFERENCES

1. J. A. Hackwell, D.W. Warren, et al., "A low resolution array spectrograph for the 2.9 to 13.5 micron spectral region", *Proceedings SPIE*, Vol **1235**, p. 171 (1990).

2. P. D. LeVan, "Capabilities of the AFGL Mosaic Array Spectrometer", *Publication of Astronomical Society of the Pacific*, Vol. **102**, pp. 190-199, 1990.

3. D. J. Schroeder, "Diffraction grating instruments", in *Methods of Experimental Astrophysics*, Vol. **12**, N. Carleton, ed., 1974.

4. M. Reine, et al., "Independently accessed back-to-back HgCdTe photodiodes: a new dualband IR detector", *J. Electronics Materials*, Vol. **24**, No 5, pp. 669-679, 1995.